Research Note

A Chamber-Free Method of Heating and Cooling Grape Clusters in the Vineyard

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A device was constructed to heat and cool grape clusters (*Vitis vinifera* L.) in the vineyard as part of a larger study on sunscald and color development in wine grapes (cv. Merlot). Selected sunlit clusters were cooled to the temperature of shaded clusters; likewise, several shaded clusters were heated to the temperature of sunlit clusters. Cooling was achieved by forced convection via a 1525-W, commercially available air conditioner. Hot air was generated using 1.4-Ω (100-W) resistance elements. Heated or cooled air was blown across fruit clusters at about 1.9 m·s[1] producing up to a 10°C change in cluster temperature. Cluster temperatures were interrogated every five seconds to activate or deactivate heaters and/or cooling fans as needed. The temperatures of sunlit and shaded clusters were used as set-points for the heated and chilled clusters, respectively. The cooling system kept clusters within 2°C of their desired target temperatures 99% of the time. Heaters achieved the same performance 97% of the time. The maximum observed increase of berry temperature above ambient air temperature (2 m above canopy) was 15.9°C for the sun-exposed side of a west-facing cluster. The control system operated continuously for 60 days between bunch closure and harvest. This heating and cooling technique can provide *in-situ* replicated measurements of berry and cluster temperatures in the field for physiological studies of ripening and ripening disorders without changing other aspects of the cluster microclimate, an unavoidable consequence of chambers or enclosures.

KEY WORDS: microclimate, canopy management, light, solar radiation,fruit temperature, berry temperature

Grape (*Vitis vinifera* L.) clusters require sun exposure to adequately develop the phenolic compounds that contribute to wine quality [6,10]. However, excessive exposure to solar radiation and/or high temperature can lead to degradation or inhibit the synthesis of these compounds [10,14]. Sunburning or sunscald of grape berries often is seen in Washington State on clusters that are exposed to solar radiation on the west or south side of the vine. Sunburned fruit have tawny skin in both red- and white-fruited cultivars. In addition, berries of west and south exposures frequently shrivel. Several decades ago, sunscald in grapes was identified as a consequence of canopy management [21]. Sunscald was observed in California on Thompson Seedless clusters that were exposed to direct solar radiation compared to those that received only diffuse solar radiation [12]. Fruit temperatures were 2.2°C to 10.5°C higher in berries exposed to direct solar radiation than in berries from completely shaded clusters. One or more of three major factors may contribute to, or directly cause sunscald in fruits, including wine grapes: *(1)* high tissue temperatures induced by solar radiation (*i.e.,* heat injury); *(2)* degradation of photosensitive pigments; and *(3)* injury induced by ultraviolet radiation [1].

To alter light exposure and/or temperature of the fruit in the vineyard, investigators have trained shoots, used artificial shading, or used leaf removal [4,5,8, 11,12]. However, these reports did not differentiate the effects of light from those of temperature on grape composition. Radler [20] heated clusters *in situ* using an electric lamp, the bulb of which was painted black to prevent the emission of visible light. Both the cluster and lamp were enclosed in a metal cylinder. Humidity, CO_2 concentration, or other environmental factors that were altered by the enclosure were neither measured nor controlled. A number of experiments were conducted in phytotrons, growth chambers, or greenhouses (*e.g.,* [10,14,17]). However, Kliewer [9] demonstrated that grape composition and ripening differed between phytotron and field conditions. In the field, overhead irrigation has been evaluated as a way to induce evaporative cooling and reduce canopy temperatures [13,18]. The color intensity of Cardinal was greatly increased and that of Carignane berries slightly increased due to evaporative cooling from overhead sprinkling [13]. The effect of supplemental irrigation on berry composition was not accounted for.

To more fully understand the mechanisms of color development and sunscald in grape berries, it is important to separate the effects of solar radiation from those of temperature in the natural environment. The objective of this research was to separate the effects of solar radiation from those of temperature in color development and sunscald in red-fruited wine grapes, *in situ*, without using a chamber or enclosure to manipulate cluster temperature. This paper describes the design and operation of a forced convection system used to

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control cluster temperature for the evaluation of berry composition under full exposure to solar radiation and under shade.

Theory: The temperature of a grape berry or cluster is a function of its energy balance: the exchange of energy between the cluster and its environment, which generally is dominated by shortwave (*i.e.*, solar) radiation and by convection, the transfer of heat between the cluster and moving air. In full sun (≈1000 $W \cdot m^{-2}$) and at wind speeds from 0.5 to 4 $m \cdot sec^{-1}$, one could expect mature, single berries to be 7°C to 12°C above ambient air temperature, and berries in tight clusters to be 11°C to 16°C above the ambient temperature [23]. During the day, the input of energy to a cluster is predominantly solar radiation, while the chief mechanism of dissipating that energy is convection. Accordingly, to study the effects of solar radiation and temperature on berry ripening, two requirements should be met: *(1)* maintenance of incident levels of solar radiation; and *(2)* use of forced convection (*i.e.*, moving air) to manipulate berry or cluster temperature. Any experimental apparatus should minimize the disturbance of the natural cluster environment and not dampen the dynamic response of the system to changes in environmental variables.

Systems designed to control some aspect of the plant environment often rely on placing a chamber around a plant organ, a whole plant, or a community of plants. Several disadvantages of chambers precluded their use in our study. Chamber materials decrease solar radiation incident upon the experimental surface. For example, a 1.5-mm thick (6-mil) UV-resistant polyethylene that covered a large (4.5-m d) chamber reduced irradiance by 10% [7]. Acrylic plastic (*e.g.*, Plexiglas™), a common material for portable photosynthetic chambers, reduces visible light by 8% when new; any pitting or abrasion of the surface under normal field conditions further reduces irradiance inside the chamber [3]. Chamber materials also may alter the quality of light they transmit. This could have consequences for color development because anthocyanin synthesis may be sensitive to the ratio of red to far-red wavelengths [15].

More importantly for our study, chambers alter the boundary layer properties of the plant or plant part inside. Enclosures also impose a system lag in addition to any biological lag in response to environmental change [16]. The boundary layer resistance to heat transfer directly influences surface temperature, convection, and the time constant of related physiological processes [2]. It varies directly with the dimensions and roughness of the surface, and inversely with wind speed and turbulence [19]. Chambers, even when aspirated, alter wind speed, the scale of turbulence, and turbulence intensity from that in the undisturbed environment. During the day, ventilated chambers generally have lower convective heat transfer than outside, causing elevated temperatures. In a large (46 m^3), well-ventilated chamber (1.7 chamber volumes$\cdot min^{-1}$), air temperature at midday was consistently 5°C above ambient [7]. By contrast, at night if the outside air is still, the chamber's ventilation rate may lead to artificially high rates of convection and temperatures held below ambient. Small chambers made of materials with low thermal conductivity, such as acrylic plastics, may make it more difficult to control the temperature of the enclosure [16].

Consequently, because a grape cluster's energy balance is dominated by solar radiation and convection, we rejected the use of chambers and chose to rely on forced convection as our primary means of heating and cooling. The system described below was designed to achieve our goals of controlling cluster temperature with minimal compromise to the cluster's microclimate.

Materials and Methods

The study was conducted during the 1999 growing season at the Irrigated Agriculture Research and Extension Center in Prosser, Washinton, USA (46.30° N, 119.75°W) in a 1.2-ha vineyard block planted in 1983. The experimental area was a block of *Vitis vinifera* L. cv. Merlot, comprising four rows of 13 vines each, oriented N-S. Vine spacing was 3 m between rows and 1.8 m within rows. Vines were double-trunked, trained to a bilateral cordon at 1.2 m, and spur-pruned. Each cordon was treated independently of its mate in terms of sunlight exposure on the clusters. Clusters of a given cordon were either shaded or sun-exposed by positioning shoots to the side of the canopy that was to be shaded. Shoots were brought over the "wind" wire (1.5 m) and tied to a catch wire (1.2 m) that was parallel to the cordon and wind wires. Because one layer of *Vitis vinifera* leaves will absorb 80% to 90% of incident solar radiation [22], this natural shading technique was expected to allow only diffuse light to strike the shaded clusters. All experimental clusters were on the west side of the canopy. Four clusters were monitored in each of six treatments: *(1)* sun exposed (sun-reference); *(2)* shaded by shoots (shade-reference); *(3)* sun exposed and chilled to shaded temperature (cooled-

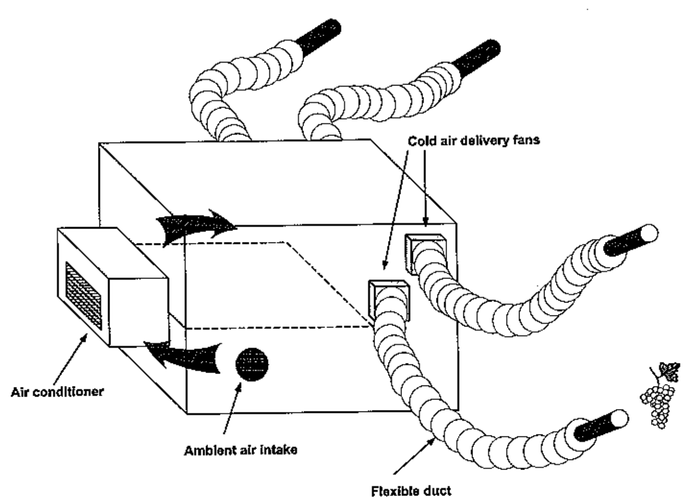

Fig. 1. Schematic diagram of the apparatus for cooling grape clusters by forced convection.

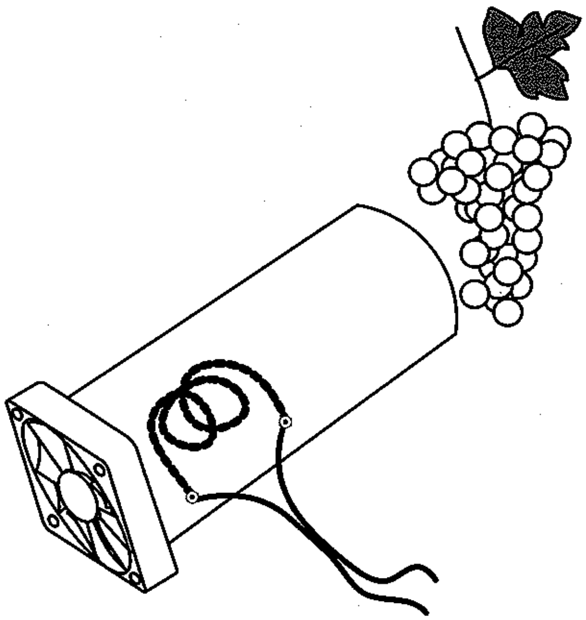

Fig. 2. Schematic diagram of the forced-air delivery tube used for heaters, chillers, and the ambient air blowers. Shown is the resistance element installed in heater tubes.

sun); *(4)* shaded and heated to sun-exposed temperature (heated-shade); *(5)* sun exposed with ambient air blown on cluster at same rate as chilled air (blower-sun); and *(6)* shaded with ambient air blown on cluster at same rate as heated air (blower-shade).

The blower-sun and blower-shade treatments served as controls for the effects of forced convection.

A standard, room-size air conditioner (110 V, 1525 W) was mounted in a 1.8 m^3 insulated enclosure, creating a cold-air reservoir (Fig. 1). The air conditioner was run continuously, with the thermostat set to start the compressor at 20°C. Flexible, insulated ducts (8.2 cm i.d.) delivered air from the reservoir to insulated, PVC (polyvinyl chloride) delivery tubes (8.2 cm i.d.). Heaters (100-W) powered by 12-V DC supplies were constructed from 1.4-Ω resistance wire mounted inside PVC delivery tubes identical to the chiller tubes (Fig. 2). Blower tubes were identical to the heater delivery tubes, but lacked a heating element. Heaters, coolers, and blowers were set ≈ 10 cm below the clusters, on the southwest side, and directed at a 45° upward angle toward the cluster (Fig. 3). Delivery tubes did not shade any part of the cluster. Hot, cold, or ambient air was blown onto the clusters (0.6 $m^3 \cdot min^{-1}$) with the aid of in-line fans and variable speed control, installed at the lower end of the delivery tube. Typical exit velocity was 1.9 $m \cdot sec^1$, giving mass flow rates of 0.7 $kg \cdot min^1$.

"Cluster" temperatures were approximated by the average temperature of four berries (described below) facing the canopy exterior and spaced evenly along the vertical axis of a cluster. Berry temperatures were interrogated every five seconds by a programmable datalogger (CR-10X, Campbell Scientific, Logan, UT) and averages computed for the four sun-reference and four shade-reference clusters. If the temperature of a given heated-shade cluster was below that of the sun-reference average, the heater was turned on. Likewise, if the temperature of a cooled-sun cluster was higher than that of the shade-reference average, the chiller fan to that cluster was turned on. Therefore, each chilled or heated cluster was controlled independently but referenced to an average shaded or sunlit cluster temperature, respectively. Fans directing ambient air onto the blower-sun clusters turned on when their companion cooled-sun clusters were being chilled. Similarly, the blower-shade fans turned on with the corresponding heated-shade clusters. Switching was controlled by the datalogger and a relay power controller (SDM-16AC, Campbell Scientific, Logan, UT). Data were averaged and stored at 12-minute intervals. The fraction of a 12-minute interval during which the heater, cooler, or blower was "on" also was recorded for each cluster.

Temperatures were measured with fine wire, type T (copper-constantan) thermocouples (36 American Wire Gauge [AWG]) wired in parallel. Junctions were inserted just beneath the berry skin, along the berry equator and on its southwest side. The wire protruding from the berry was fixed to the skin with a drop of water-based, household glue. No necrosis was observed at thermocouple entry points. All measurements were replicated four times. Multiplexers designed specifically for thermocouples (AM25T, Campbell Scientific, Logan, UT) were used. Ambient air temperature was measured 2 m above the canopy by a shielded, aspirated, fine wire thermocouple (36 AWG; Type T). Global irradiance was measured by a pyranometer (model 8-48, Eppley Laboratories, Newport, RI). Irradiance at the fruiting zone was measured parallel to shaded and sun-exposed cordons by 1-m long tube solarimeters (model TSL, Delta-T Devices, Cambridge, UK). Signals from the air temperature sensor and pyranometers were scanned every 10 seconds and averaged at 12-minute intervals. Data were collected for 60 days, from bunch closure to harvest. Wind speed at 2 m was measured by a 3-cup anemometer (Wind Sentry, R. M. Young, Traverse City, MI) at the PAWS (Public Agriculture Weather System) station at the research facility. Signals were recorded every 10 seconds and data averaged every 15 minutes. The albedo, or solar reflectance (0.4 to 1.3 μm) of representative clusters (n = 6 to 7) was measured with a temperature-compensated, portable spectroradiometer (Field Spec Pro FR, Analytical Spectral Devices, Inc, Boulder, CO) for green clusters, post-veraison clusters, and mature clusters at harvest.

Results and Discussion

At the Prosser location, growing degree days (GDD) for the 1999 season totaled 1247 (10°C base). Average GDD for 1954 through 1999 are 1392, placing the 1999 season as the eighth coolest. The heating/cooling system operated without interruption from bunch closure at day of year (DOY) 225 to harvest (DOY 285). Prior to

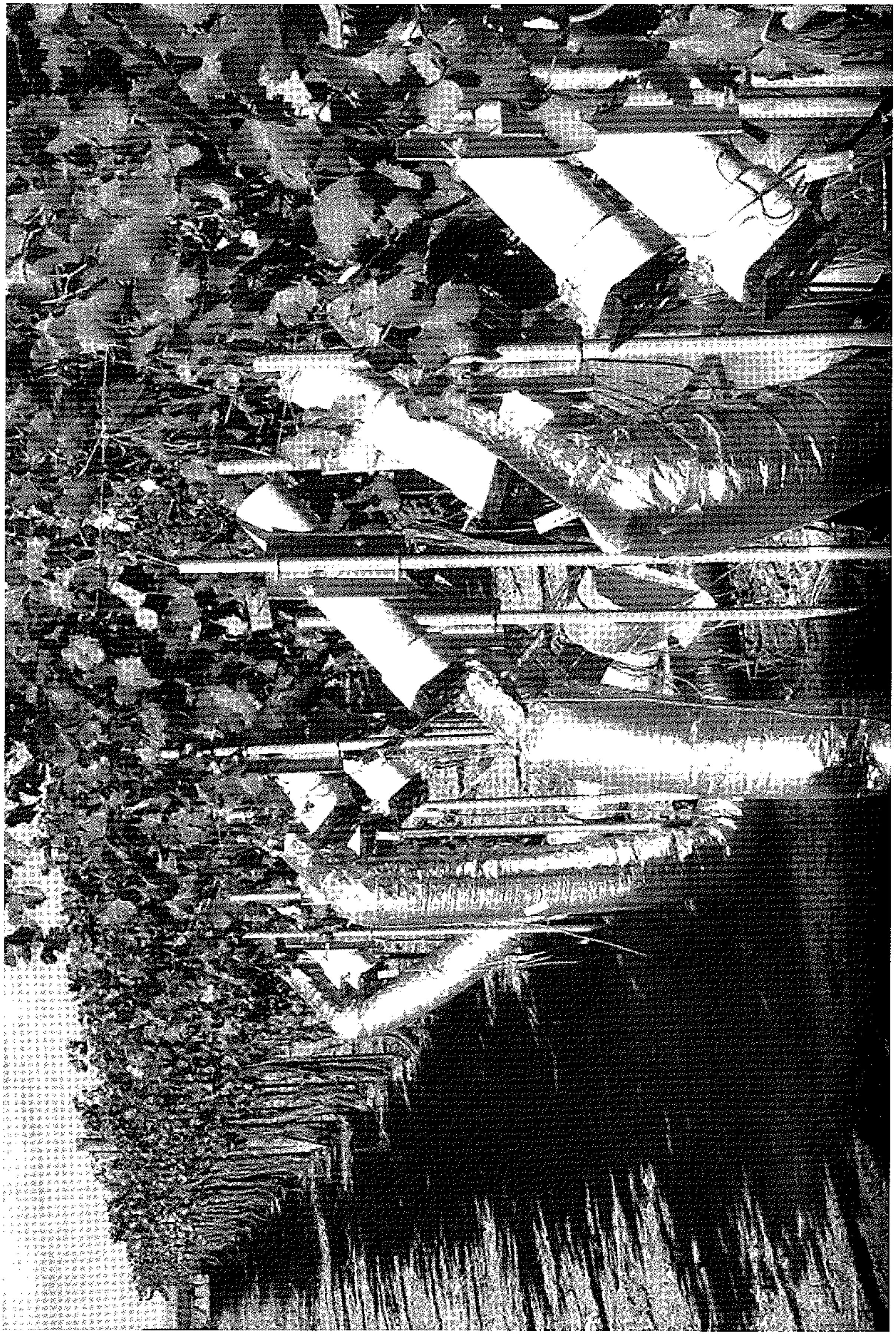

Fig. 3. Delivery system for heated and cooled air shown in the experimental vineyard.

installation, the air conditioning unit was tested in the vineyard. During the test, the average drop in air temperature from inlet to outlet was 6.5°C. Given a mass flow rate of 0.7 kg·min^{-1}, we calculated a potential heat transfer rate of 75 W, well above an estimated 10-W maximum solar load on the projected surface of a sunlit cluster, assuming a maximum irradiance of 1000 W·m^{-2}. However, because our delivery system was designed so that the cluster would not be isolated from the environment, we anticipated an inherent inefficiency in heat transfer. It is likely that some of the chilled air mixed with and was carried off in the free stream before reaching the cluster surface. Air exiting the delivery tubes was consistently 19.2°C. During the 60-day experiment, the temperature difference between inlet and outlet air, and between outlet air and berry varied, thus changing the absolute potential for heat transfer at the cluster surface. This was compensated for by longer intervals of cooling during times when the clusters were significantly warmer than their shaded reference. The system's high rate of mass flow ensured excellent overall performance over a range of temperature differences (*e.g.*, Fig. 4A). The only anomalies observed with the cooling system occurred on a few occasions when berries were below 20°C, the temperature at which the compressor had been set to switch on (data not shown). If the compressor was not

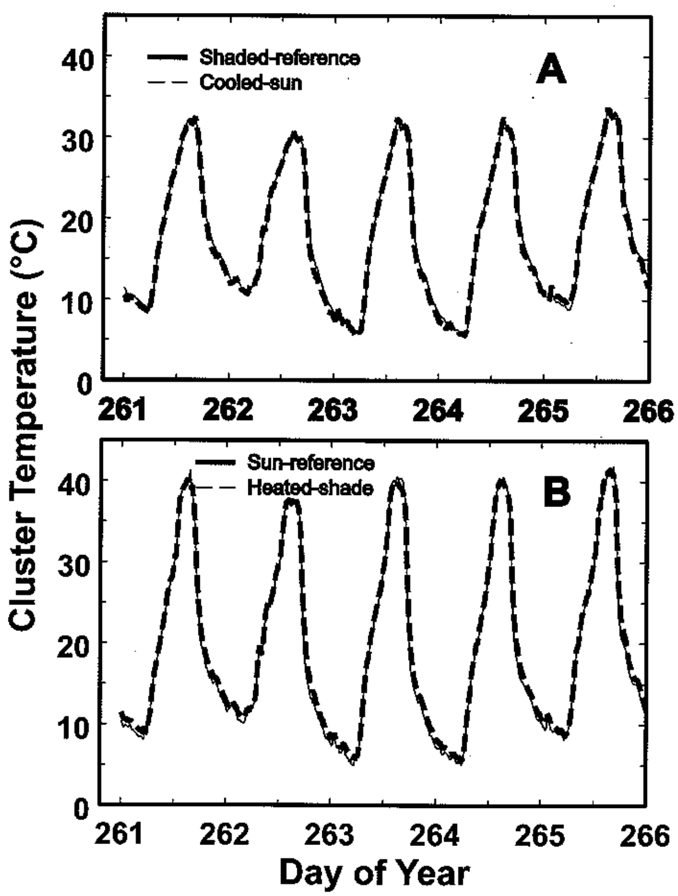

Fig. 4. Diurnal pattern of temperature for cooled (A) and heated (B) berries and their reference clusters, during a 5-day period following veraison.

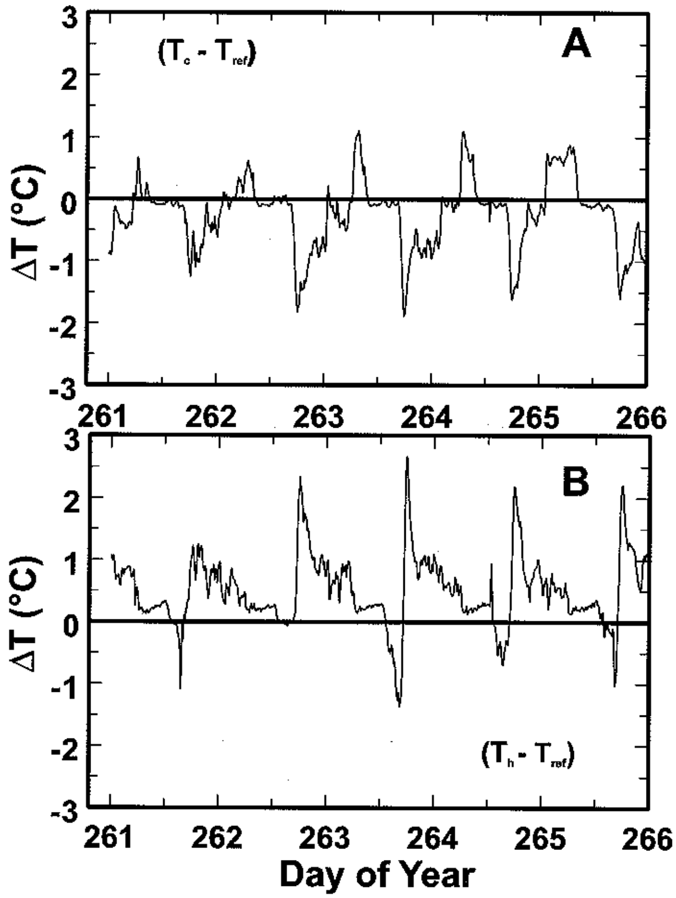

Fig. 5. Difference in temperature (ΔT) between cooled berries (T_c), heated berries (T_h), and their respective reference clusters (T_{ref}) during same period as in Fig. 4.

"on" but the berries were warmer than their shaded reference, then ambient air was blown onto "chilled" clusters. The system will be upgraded with the addition of a programmable thermostat that links the compressor switch to the temperature of the shaded reference cluster rather than to an arbitrary set point.

The heaters performed as well as the chilled-air system (Fig 4B). The heater switches were linked directly to the temperature of the sunlit reference cluster, thus avoiding the set point problem we encountered with the air conditioning compressor. During the 60-day experiment, heated berries were kept within 2°C of their sunlit reference 97% of the time and cooled berries were kept within 2°C of their shaded reference 99% of the time. Typical diurnal patterns of temperature control are shown for a post-veraison period (Fig. 5). Both heated and cooled berries agreed most closely with their reference clusters during the morning, before direct solar radiation impinged on the sun-exposed clusters. During the late afternoon, when irradiance at sunlit clusters was highest, the cooled berries were slightly cooler and the heated berries were slightly warmer than their references.

During daylight hours, heaters and coolers operated for various fractions of a measurement interval (12 min; Fig. 6) depending on solar heating and wind

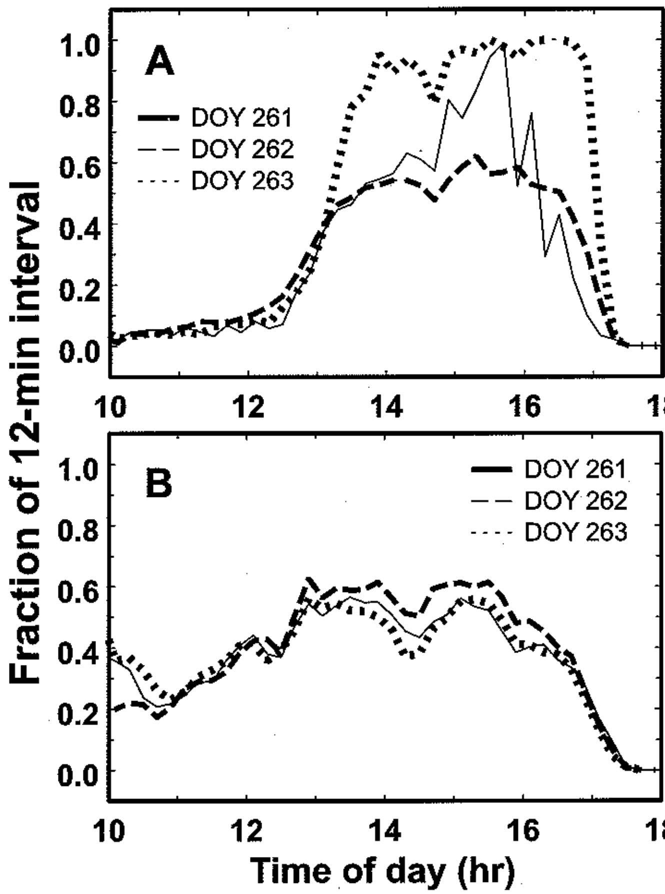

Fig. 6. Fraction of a 12-minute data collection interval during which the heated (A) or chilled (B) air was blown onto experimental clusters, during mid-day hours on three days during the experiment with clear skies, similar global irradiance, and different wind speeds.

speed. The heated clusters, which were fully shaded, show the effects of varying wind speeds and potential advection and free convection from the soil surface. Advection refers to the horizontal transfer of heat by moving air and is directly related to wind speed. Bare, dry soil, which is common in eastern Washington vineyards, drives a potentially large amount of advection and free convection because its surface can be as much as 20°C higher than the air immediately above it [24]. On DOY 263, mean wind speed between 1000 and 1800 hr was 0.6 m·sec[1]. The heated clusters, which were not exposed to direct solar radiation, probably gained some heat from free convection but very little from advection. Therefore, the heater device operated longer to maintain the shaded cluster at an elevated temperature (Fig. 6A). Conversely, on DOY 262, mean daytime wind speed was 1.9 m·sec[1], with the highest midday values >3 m·sec[1]. The shaded berries probably were warmed slightly by advection and required less external heating from our system. Of the three days shown, the differences in temperature between sunlit and shaded berries were inversely related to wind speed. Maximum differences occurred around 1530 hr. All three days were clear and had similar global irradiance (Fig. 7A). By comparison, the cooling system chilled berries whose temperatures were due primarily to radiative heating; advection represented a much smaller fraction of the cluster's energy balance. Thus, the fraction of the measurement interval that the cooling system was "on" was less substantially related to wind speed (Fig. 6B). On DOY 263, when the clusters were subjected to less advected energy, the cooling unit operated for slightly less time than on a comparative day with relatively high wind speeds (DOY 262).

Given the low level of solar radiation reaching the fruiting zone of shaded clusters (Fig. 7A), it is reasonable to assume that radiation striking the shaded berries was almost entirely diffuse. Because the experiment was conducted on the west side of the canopy, sun-exposed clusters were subject to near-ambient solar radiation only in the afternoon. At midday, sun-exposed berries consistently were 8°C to 10°C warmer than shaded berries (Fig. 7B) and up to 16°C warmer than the air above the canopy (data not shown). Typical daytime temperatures for sunlit berries were between 8°C and 15°C above ambient, which is within the range of previously reported values (*e.g.,* [12,23]). That the clusters were lower than air temperature at night is due to negative net radiation and low wind speeds (<1 m·sec[1]; data not shown).

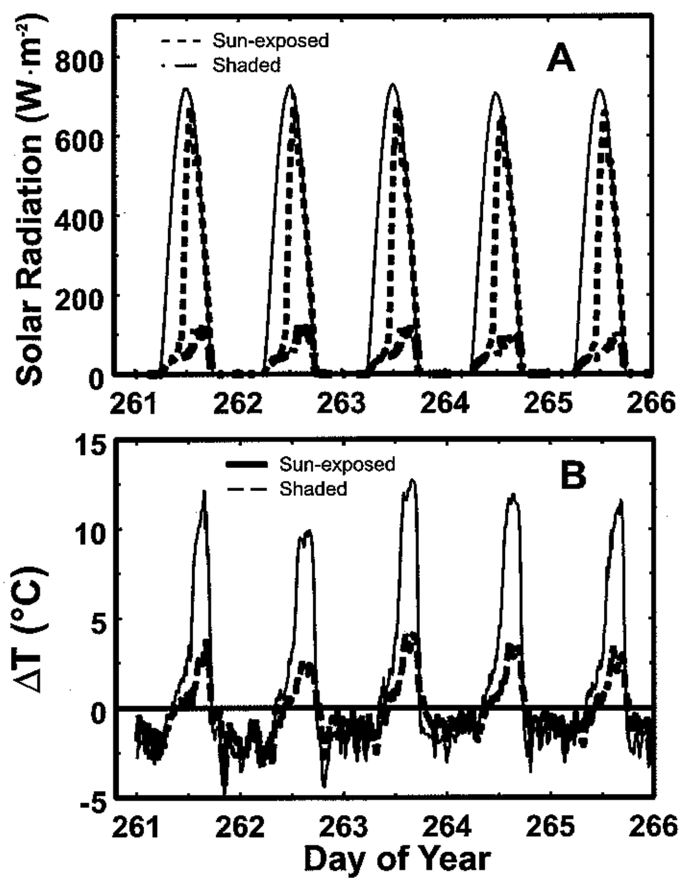

Fig. 7. (A) Diurnal course of solar radiation during the same period as Fig 4. The solid line is global irradiance. "Sun-exposed" and "shaded" refer to incident radiation at the height of the fruiting zone along cordons with fruit fully exposed to the sun or fully shaded by the canopy, facing west. (B) Diurnal course of the differences between ambient and cluster temperature for sun-exposed and fully shaded berries facing west during the same period as in (A).

Shortwave reflectance (dimensionless) of the clusters decreased from 0.17 when berries were green to 0.14 just after veraison, and 0.13 at harvest, suggesting that solar heating might not have varied greatly over the course of the experiment. Maximum elevations of berry temperature above ambient were similar from pre-veraison through harvest. However, from DOY 225 to DOY 285, peak global irradiance gradually declined from ≈850 W·m² to ≈600 W·m². During the same period, day length decreased from 14.1 hours to 9.5 hours. Peak irradiance at the cluster was the primary determinant of the daily maximum rise in berry temperature. However, day length determined the duration of solar heating, which in turn influences berry development. After veraison, berries on shaded clusters often were >30°C while sun-exposed berries exceeded 40°C (Fig. 4). Studies are in progress on the effects of the treatments listed in this paper on berry composition, with a focus on phenolic compounds.

In conclusion, the heating and cooling system described above achieved our goal of controlling berry temperatures *in situ* with the least practical interference with the cluster microclimate. We were able to cool and heat clusters to within 2°C of target temperatures >97% of the time during the 60 days between bunch closure and harvest. This methodology should be applicable to other studies on the effects of light and temperature on berry composition in the natural vineyard environment.

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